PQ TechWatch

A product of the EPRI Power Quality Knowledge program

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Power Quality in Medium and Large Commercial Buildings

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SUMMARY

According to the European Union, 40% of all electric energy produced in Europe is used to power commercial and residential buildings. Commercial buildings include nonresidential, nonindustrial buildings such as hospitals, office and apartment buildings, hotels, schools, churches, stores, theaters, and sports arenas. Within those buildings, HVAC units, PCs, fax machines, copiers, and printers are now sharing the building wiring system with electronic fluorescent lighting, adjustable speed heat pumps, and various electronic communications equipment. While electronic-based commercial equipment increases productivity, this type of equipment can often be adversely affected by poor power quality.

Today, the quality of electric power generation, transmission, and distribution systems is very high. With the exception of conditions associated with brownouts, most utilities deliver well-regulated power to all but the most extremely remote customers. However, power dips and surges are still of concern, largely because of the potential impact for electronics damage and interference with computer operations. Another power quality issue that must be kept in mind is the production of harmonic currents by nonlinear equipment, such as office equipment, lighting, and some HVAC systems.

This *PQ TechWatch* takes an in-depth look at some of the larger components of commercial operations, including HVAC, lighting, office equipment, and elevators. The intent of this document is to show how power quality impacts commercial equipment and what mitigation techniques can be applied to minimize shutdowns and equipment damage.

About the EPRI Power Quality Knowledge program

The EPRI Power Quality Knowledge program provides a wealth of resources in well-designed, readable, and accessible formats. Paramount among these resources are documents covering a wide range of PQ topics, written not only for use by busy PQ professionals, but also to be shared with important end-use customers and internal utility managers. The program's website, www.mypq.net, is the most comprehensive electronic PQ resource available, providing 24-7 access to proven expertise via the PQ Hotline, hundreds of PQ case studies, over 200 PQ technical documents, PQ standards references, indexes, conference presentations, and a wealth of other resources.

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The proliferation in office use of electronic equipment and microprocessor-based controls has caused electric utilities to redefine power quality in terms of the quality of voltage supply rather than availability of power.

INTRODUCTION

Power quality has emerged as an important issue for the commercial customer segment. Historically, power quality issues have been the domain of electric utilities, which focused on reducing or eliminating power outages. However, the proliferation in office use of electronic equipment and microprocessor-based controls has caused electric utilities to redefine power quality in terms of the quality of voltage supply rather than availability of power. In this regard, IEEE Standard 1159-1995(R2001) *Recommended Practice for Monitoring Electric Power Quality* and its European counterpart IEC 61000-4-30 *Testing and Measurement Techniques—Power Quality Measurement Methods* have defined a set of terminologies and their characteristics to describe the electrical environment in terms of voltage quality. The table below shows the categories of power quality disturbances with spectral content, typical duration, and typical magnitude.

This document focuses on how commercial equipment is affected by power disturbances. The term *commercial building* encompasses all buildings other than industrial buildings and private dwellings. It includes office and apartment buildings; hotels; schools; churches; steamship piers; air, railway, and bus terminals; department stores; retail shops; government buildings; hospitals; nursing homes; mental health and correctional facilities; theaters; sports arenas; and other buildings serving the public directly.

Major Uses of Energy in Commercial Buildings

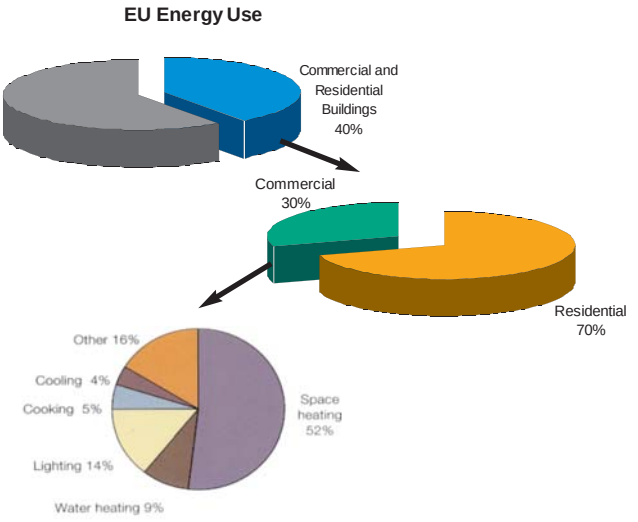
Each principal building activity has its own set of characteristics (energy sources, equipment, number of workers, hours of operation) that contribute to total energy use. European research shows that 40% of the total energy used in the European Union (EU) is used in the residential and commercial building sector, and the breakdown of energy usage within that sector is shown below.[1] Commercial buildings alone account for about 12 percent of EU energy use. However, the study doesn't show how the growth of the Internet and the proliferation of digital equipment has changed the dynamics of the electrical environment.

Categories of Power Quality Variation

Categories	Typical Spectral Content	Typical Duration	Typical voltage Magnitudes
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5 ns rise	< 50 ns	
1.1.2 Microsecond	1 µs rise	50 ns–1ms	
1.1.3 Millisecond	0.1 ms rise	>1 ms	
1.2 Oscillatory			
1.2.1 Low Frequency	< 5 kHz	0.3–50ms	0–4 pu
1.2.2 Medium Frequency	5–500 kHz	20 µs	0–8 pu
1.2.3 High Frequency	0.5–5 MHz	5 µs	0–4 pu
2.0 Short duration variations			
2.1 Instantaneous			
2.1.1 Sag		0.5–30 cycles	0.1–0.9 pu
2.1.2 Swell		0.5–30 cycles	1.1–1.8 pu
2.2 Momentary			
2.2.1 Interruption		0.5 cycles–3 s	< 0.1 pu
2.2.2 Sag		30 cycles–3 s	0.1–1.9 pu
2.2.3 Swell		30 cycles–3 s	1.1–1.4 pu
2.3 Temporary			
2.3.1 Interruption		3 s–1 min	< 0.1 pu
2.3.2 Sag		3 s–1 min	0.1–0.9 pu
2.3.3 Swell		3 s–1 min	1.1–1.2 pu
3.0 Long duration variations			
3.1 Interruption, sustained		> 1 min	0.0 pu
3.2 Undervoltages		> 1 min	0.8–0.9 pu
3.3 Overvoltages		> 1 min	1.1–1.2 pu
4.0 Voltage imbalance		steady state	0.5–2%
5.0 Waveform Distortion			
5.1 DC offset		steady state	0.0–0.1%
5.2 Harmonics	0–100th H	steady state	0–20%
5.3 Interharmonics	0–6 kHz	steady state	0–2%
5.4 Notching		steady state	
5.5 Noise	broad-band	steady state	0–1%
6.0 Voltage fluctuations	< 25 Hz	intermittent	0.1–7%
7.0 Power frequency variations		< 10 s	

Source: IEEE Std. 1159-1995

Energy End Uses in the European Residential and Commercial Sectors

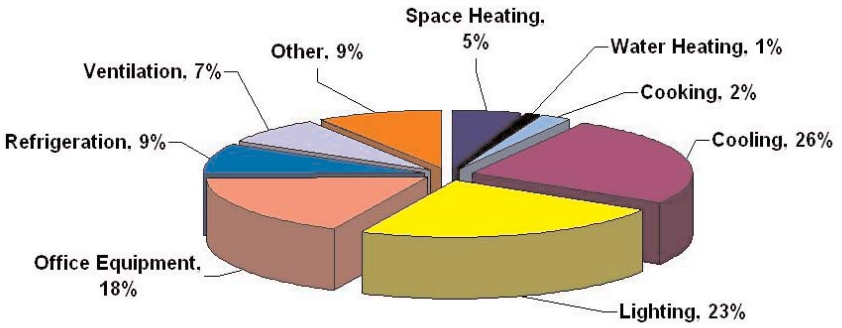


The commercial building sector accounts for 12% of total European Union energy consumption.

Source: European Commission

Unfortunately, the EU study only shows total energy use and does not differentiate electrical, natural gas, oil, and sustainable energy users. The figure below shows a breakdown of how electricity is used in commercial facilities in the United States.

Electrical Energy End Uses in the U.S. Commercial Sector



Source: Commercial Buildings Energy Consumption Survey (CBECS), Energy Information Administration (EIA)

The consequences of a disturbance may range from a minor nuisance to extensive equipment damage and loss of critical data.

Typical Electric Loads of Commercial Buildings

The systems, equipment, and facilities used to satisfy functional requirements of large commercial buildings will vary with the type of commercial building but will generally include some, or all, of the following:

- Interior and exterior lighting, both utilitarian and decorative
- Communications systems, such as telephone, telegraph, computer link, radio, closed-circuit television, code call, public address, paging, electronic intercommunication, pneumatic tube, doctors' and nurses' call, and a variety of other signal systems
- Fire pumps and sprinkler, fire-detection, and alarm systems
- Elevators, moving stairways, dumbwaiters, and moving sidewalks
- Heating, ventilation, and air-conditioning
- Garbage and rubbish storage and removal, incinerators, and sewage handling
- Hot- and cold-water systems and water treatment facilities
- Security watchmen and burglar alarms, electronic access systems
- Business machines, such as computers, calculating machines, and duplicating machines
- Refrigeration equipment
- Food handling and preparation facilities
- Building maintenance facilities
- Lightning protection
- Automated building control systems
- Entertainment facilities and specialized audiovisual and lighting systems
- Medical facilities

Power Quality Impact on Commercial Customers

Power quality variations as described in the table on page 1 affect all categories of commercial customers. However, depending on the criticality of the equipment affected, the consequence of the disturbance may range from a minor nuisance to extensive equipment damage and loss of critical data. For example, a momentary voltage dip may impact the operation of an elevator and may cause it to stop at a floor where it wasn't supposed to. In most cases, this is nothing more than a nuisance. However, the same voltage dip might instead cause an elevator controller to fail and may require a service call during which the elevator would be

unavailable. The table below shows the list of generic equipment used in the commercial sector and the associated power quality symptoms and the primary power quality disturbances affecting the equipment.

Impact of Power Quality Disturbances on Commercial Sector Electrical Equipment[2]

Electrical Equipment	Power-Problem Symptoms	Primary Power Quality Disturbance Category
Air conditioning	Premature compressor failure	Voltage variation
Audio system	Unit damage	EMI/RFI
Computerized cooking equipment	Unit damage Increased service calls	Transients
Copy machine	Touchpad damage Increased service calls	Transients
Digital scale	Unit damage	Transients/EMI/RFI
Digital thermostat	Lack of control Unit damage	Transients/EMI/RFI
Energy management	Loss of control	Transients/EMI/RFI
Fax machine	Unit damage No or poor communication	Transients/EMI/RFI
Fire/security system	False alarms Unit damage Increased service calls	Transients/EMI/RFI/voltage variations
HVAC equipment	Compressor failure Increased service calls	Voltage variation
Patient database computerized system	Data loss/data error	Voltage variation
ECG/EKG machine	Component damage Erroneous reading	Voltage variation/transients
Elevators	Component damage Increased service call	Voltage variation
Computerized reservation system	Data loss/data error	Voltage variation
Simplex clock system	Incorrect time	EMI/RFI
ATM machine	Processing unit damage Incorrect data	Transients
Gamma counter	Unit damage	Voltage variations/transients
Check approval system	Unit damage Increased service call	Voltage variation/transients
Bar code scanner	Scanner damage Wrong scanning	EMI/RFI/transients
EEG/EKG machine	Unit damage	Transients/voltage variation
Data processing	Data loss/corruption	Voltage variation
Lighting control	Unit damage Brightness or dimness in lights Flickering of lights	Transients/voltage variation

Source: EPRI TR-114240

Voltage variations such as dips, interruptions, and under- and overvoltages, both long-term and short-term, have the greatest impact on commercial sector equipment. Only the impact of voltage dips is not as critical as it is in the industrial sector. The main reason is that mission-critical equipment such as data processing centers are in most cases protected by uninterruptible power supplies (UPSs) and backup generators. In industrial processes, minor voltage dips can cause product loss, operational delays, and possibly loss of customer confidence. However, power disturbances in both the commercial and industrial sites must be considered when designing a building or purchasing and operating equipment.

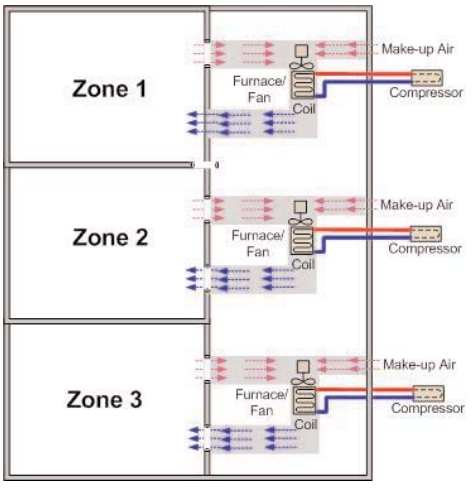
HEATING, VENTILATION, AND AIR CONDITIONING SYSTEM (HVAC)

The largest commercial building load is the HVAC system. In addition to environmental controls for personal comfort levels, an HVAC system plays a vital role for buildings with data centers, which contain servers, personal computers, uninterruptible power supplies, and network and telecommunication equipment. Critical-facility loads are those loads that are vital to the operation of the building. Types of equipment that fall into the critical-facility group include air-conditioning systems, process cooling water (chillers and water pumps), and ventilation systems.

Air-Conditioner Systems

Split- or packaged air conditioning systems are common in commercial buildings with multiple zones. The split-air systems are composed of two major components: the outdoor compressor/fan and the indoor furnace/ventilation units. In the split-air conditioner configuration, one HVAC unit is used to control the environment of one zone, as shown in the figure below.

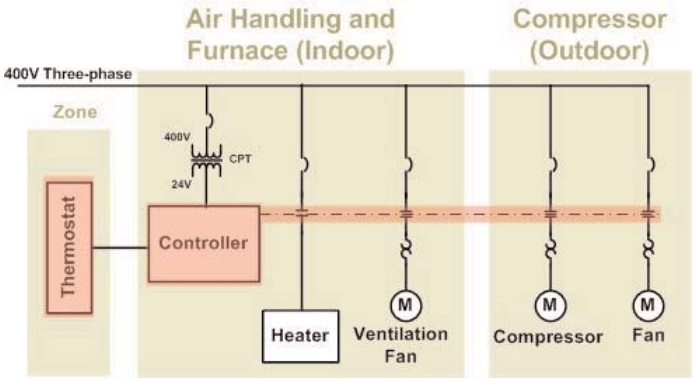
Split-Air HVAC Configuration



One HVAC system controls one zone in commercial buildings with multiple zones.

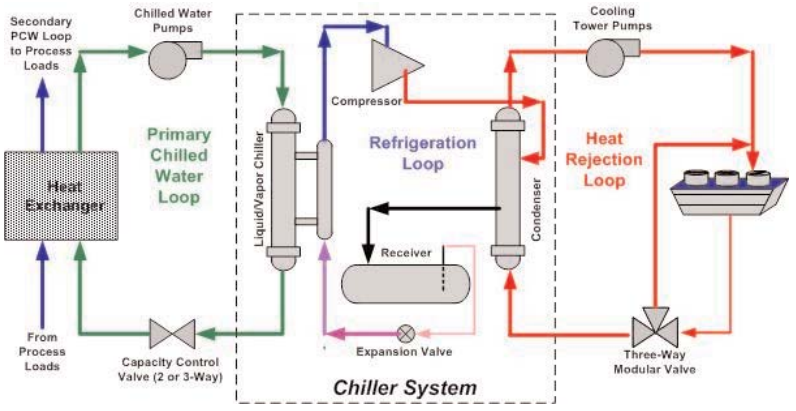
The power quality events that most adversely affect this type of conditioner system are voltage dips and interruptions. Voltage dips can cause any or all contactors and relays to change state and can also cause misoperations of controls. A single-line diagram of a typical split-air conditioning system is shown below.

Components Sensitive to Voltage Dips on a Split-Air Conditioning System



Components sensitive to voltage dips are highlighted in red.

Chilled-Water Process Loop



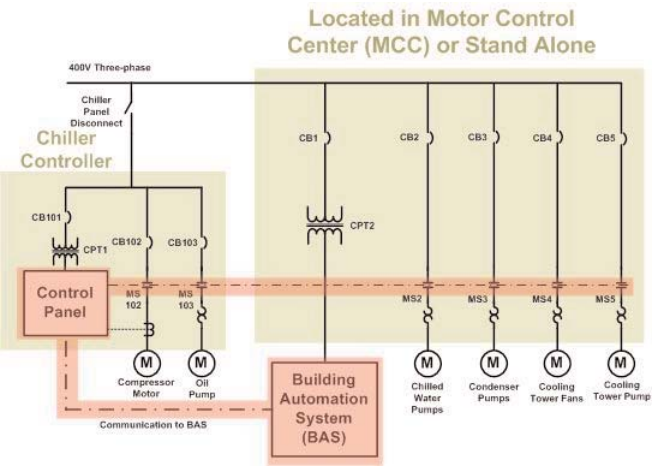
Chilled water systems are used to cool equipment and products in commercial manufacturing processes.

Process Cooling Water (Chillers and Water Pumps)

Buildings requiring between 50 and 5000 tons of energy utilize chillers to provide process cooling water to air handling units throughout the building. The two basic refrigeration system methods are chilled water or direct expansion (DX). In the chilled water system, the cooling media that interfaces to the airside heat transfer coil is chilled water. In a direct expansion system, the evaporator coil interfaces directly to the refrigeration system loop, eliminating the use of chilled water. In commercial buildings that support manufacturing processes, cooling water plays a vital role in cooling equipment and products. The process loop shown in the figure at bottom left is a general representation of a process cooling water system

Similar to both the split-air conditioner and ventilation systems, the electrical components of a chilled water process are also sensitive to voltage dips and interruptions. An example single-line diagram is shown below.

Components Sensitive to Voltage Dips on a Process Cooling Water System



Components sensitive to voltage dips are highlighted in red.

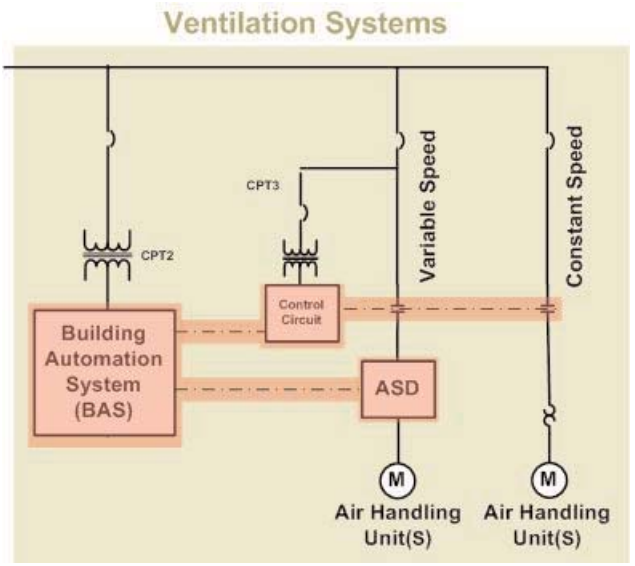
The tolerance of HVAC systems can be greatly improved by protecting all control circuits from being exposed to voltage dips and interruptions.

The voltage-dip-sensitive components of a chilled water system are the chilled controller, C control relays and contactors, motor starters, and the motor protection relay.

Ventilation Systems

The function of ventilation systems is to move conditioned air. Volume requirements set by ventilation standards dictate the size and number of motors required for a given space. Ventilation fans are either driven by a constant speed or variable speed motor. A variable-speed fan is more energy efficient than a constant-speed fan. Both types of fan configurations are shown in the single-line diagram below. Components of the ventilation system sensitive to voltage dips are highlighted in red.

Variable- and Constant-Speed Ventilation Fan Configurations



Components sensitive to voltage dips, such as the adjustable speed drive (ASD), are highlighted in red.

Protection of HVAC Voltage-Dip-Sensitive Components

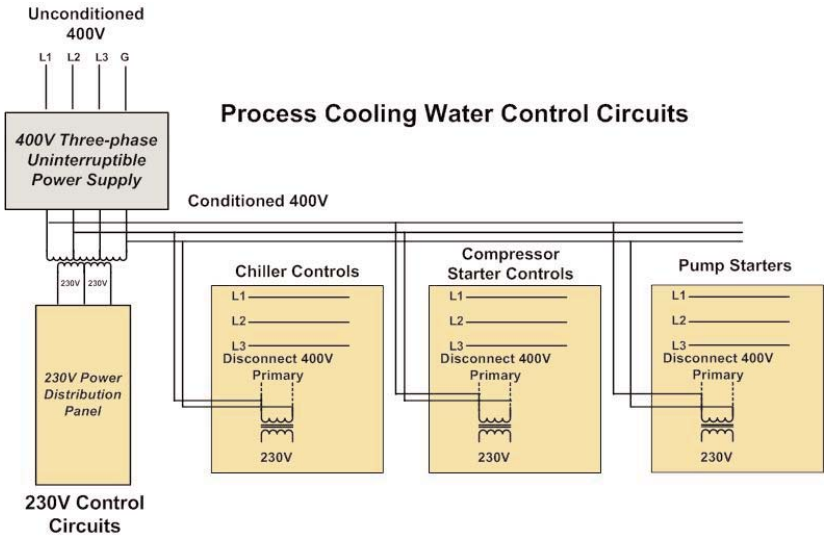
The tolerance of HVAC systems can be greatly improved by protecting all control circuits from being exposed to voltage dips and interruptions. Control circuits can be protected by powering all control circuits from a conditioned power source. The two most common techniques to provide conditioned power to all control circuits are:

- Central power conditioning
- Discrete power conditioning

Central Power Conditioning Technique

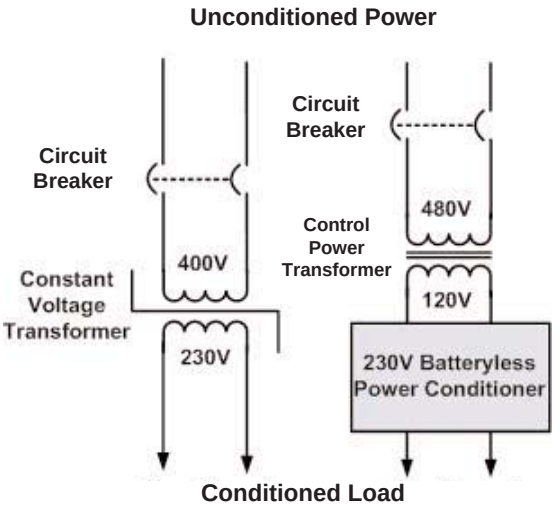
If there are a number of control circuits requiring conditioning, a centralized power conditioner can be used to condition all control circuits, as shown in the figure on the top of the next page. Due to the high maintenance needs of many small battery-based power conditioners, they are not recommended for critical process systems. However, when a centralized conditioner can be used, a battery-based conditioner such as a UPS is recommended since maintenance for only one unit is required. If this option is applied, safety needs to be considered because the equipment will be powered by a separate power source. Be sure to follow all local codes for external power sources.

Centralized Power Conditioner Solution for Individual Control Circuits



A typical process cooling water control circuit.

Power-Conditioning Solutions for Control Circuits Powered by Constant Voltage Transformers



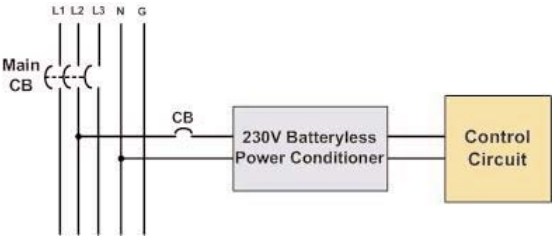
Constant voltage transformers can condition power for control circuits.

Discrete Power Conditioning Technique

When critical process machine control circuits are powered by control power transformers (CPTs), the CPT can be replaced with a constant voltage transformer, or a single-phase batteryless power conditioner can be added to the secondary between the load and the transformer. The two circuits in the figure on top right show both CPT options.

If the control circuits are powered by a line-to-neutral (L-N) connection, all line-to-line control circuits must be identified and conditioned by a power conditioner. The line-to-line control circuit in the figure on bottom right is protected by a single-phase batteryless power conditioner installed between the circuit breaker and the control circuit.

Line-to-line (L-L) Control Circuit Power-Conditioning Solution



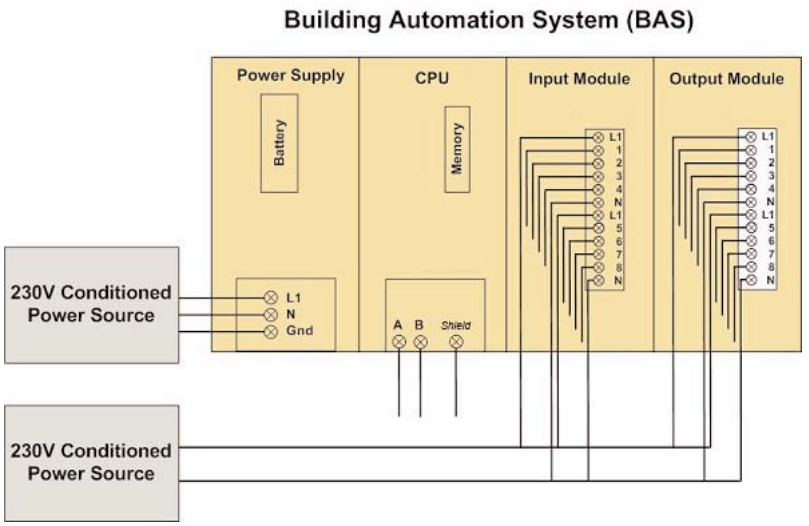
Power conditioning can be configured line-to-line.

Building Automation Systems

In large commercial buildings, the building automation system (BAS) controls all HVAC components. The BAS is used to automate the air conditioning process and to increase the energy efficiency of all systems. There are many different types of BAS configurations and methods of control; however, all types of controllers have the same basic elements. BAS units are

composed of a central processing unit (CPU) powered from either an internal or external DC power supply and all have either AC or DC I/O used to interpret inputs and outputs. The BAS can be protected against voltage dips and interruptions by conditioning all power to the BAS power supply and I/O as shown in the figure below.

Building Automation System Power-Conditioning Technique



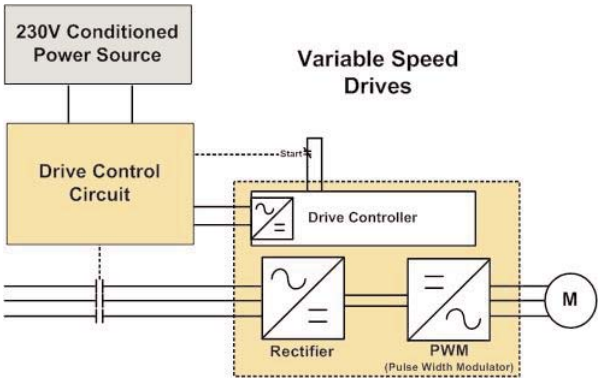
Using line-to-line power conditioning for building automation systems.

Besides protecting all power to the BAS, make sure that the CPU's battery used to maintain the program in the event of power interruption is working properly. Typically the life span of these types of batteries is two years. To be safe, all BAS batteries should be replaced on a yearly maintenance basis.

Variable-Speed Drives for Ventilation and Water Pumps

Variable-speed drives in commercial buildings are used to power ventilation fans and water pumps. Voltage dips can enter the drive and affect its performance through three different areas shown in the figure below. The first and typically the most sensitive to dips is the drive's control circuit. The control circuit can be protected by following the centralized or discrete power conditioning technique described herein. The second component of the drive sensitive to dips is its internal controller. Depending on the drive's configuration, when access to the internal control circuit and controller are made available, this circuit should be powered from a conditioned source.

Variable-Speed Drive Power-Conditioning Solution



Power conditioning for motor drives can often focus on the control circuitry only.

The third component of a drive sensitive to dips is the rectifier/inverter circuit. When the rectifier is subjected to voltage dips or interruptions the DC voltage output level is changed. The DC voltage change is dependent on the magnitude and duration of the voltage dip event. If the DC voltage level meets or exceeds a determined level (called the undervoltage trip point), the drive will stop and will need to be restarted, either manually or automatically.

In most cases, drive manufacturers give users access to basic microprocessor program parameters to configure it for a particular application.

A low-cost or perhaps no-cost method of reducing trips caused by undervoltage faults is through software configuration setting changes. This technique applies to AC and DC drives. The vast majority of drives in use today have rectifiers that convert AC power to DC. Some drives use inverters to create a variable-voltage, variable-frequency AC waveform to control AC motors. Others use the DC power directly to control motors in DC servo and DC drive systems. These types of drives are similar in that they have a microprocessor program that governs the AC-to-DC conversion processes and motor-control circuits. In most cases, drive manufacturers give users access to basic microprocessor program parameters so that the drive can be configured to work in the user's particular application.

A drive's programming parameters associated with reducing the effect of voltage dips are seldom described in one section of the user manual. The table below lists some common programming parameters that when enabled, disabled, or changed may improve the drive's performance to voltage dips. The parameter names in the tables may differ from those used by manufacturers, so each table includes a functional description.

Automatic restart and reset parameters control the starting and stopping behavior of the drive and can be adjusted to prevent nuisance tripping of a drive and the subsequent shutdown of a process.

Programming Parameters That Can Improve a Drive's Tolerance of Voltage Dips

Automatic Reset and Restart Functions

Parameter	Parameter Description
Automatic Reset	This parameter allows the drive to automatically reset some fault conditions, such as DC link undervoltage or overvoltage, without the need for operator/user intervention. This feature is used in conjunction with Automatic Restart.
Automatic Restart	This parameter defines the method in which the drive automatically restarts after a fault condition is over. Automatic Restart operations may only be used as outlined in NFPA 79. Equipment damage and/or personal injury may result if the Automatic Restart parameter is used in an inappropriate application.
Automatic Restart Attempts	This parameter allows the user to program the number of times that the drive attempts to restart the motor after an undervoltage or other fault condition.
Automatic Restart Interval	This parameter is a user-specified time delay between the automatic restart attempts and the end of the fault condition.
Automatic Restart Time Delay	This parameter is a user-specified time delay between the end of the fault condition and an automatic restart.
Restart at User-Defined Frequency Setting	When the drive senses a DC link undervoltage condition, the drive shuts down the inverter, allowing the motor to coast. The motor is allowed to coast until the undervoltage condition ends. The drive then restarts the motor at a user-defined frequency setting. If the restart frequency is significantly higher or lower than the frequency of the motor, large inrush currents, torque, and speed transients could be induced on the motor (and load). The restart frequency setting, the acceleration rate, deceleration rate, current limit, and torque limit should be considered when using this feature.
Flying Restart	This parameter is similar to the parameter above with one major exception: Rather than restarting at a pre-defined frequency setting, the drive uses a search algorithm to determine the motor speed. Once the speed is recognized, the drive reaccelerates the motor to the desired operating point. The odds of the motor and load experiencing extreme current and torque transients are greatly reduced.

Motor-Load Control Functions (Flying Restart)

Parameter	Parameter Description
Kinetic Buffering	When the drive senses a DC link low-voltage condition, the drive uses the combined motor-load inertial energy to maintain a factory-programmed DC link voltage inside the drive by applying a braking force to the motor. This feature does not create a potential for extreme current or torque transients.
Motor Voltage Compensation	When the drive senses a DC link low-voltage condition, the drive's controller changes the inverter firing timing sequences to compensate for a reduced DC link voltage. The objective is to maintain as close as possible the desired output voltage for operating the motor and load.
Controlled Deceleration and Acceleration	When the drive senses a DC link undervoltage condition, the drive begins to decelerate the motor at a user-defined rate. When the undervoltage condition ends, the drive reaccelerates the motor back to the desired operating point. This feature is often used in processes with multiple drives operating in succession, where all drives are expected to operate in unison to maintain process quality. This feature works well for common DC bus drive systems.

Phase-Loss and DC Link Undervoltage Functions

Parameter	Parameter Description
Input Phase Loss	The input phase-loss-detection circuit monitors either the input phases or DC bus current ripple and activates when one of the input phases is lost. In some drives, an input-phase loss alarm will be generated if the duration of the phase loss is greater than the input Phase Loss Delay setting.
Input Phase Loss Delay	This parameter controls the delay time in which an input phase loss must be present before a fault is generated. If the input phase returns to nominal before the delay time, a fault will not be generated.
DC Bus Undervoltage Limit or Undervoltage-Detection Level	Some drive manufacturers allow users to change the DC bus undervoltage trip point. By lowering the trip point, drives and processes may ride through longer and deeper voltage sags without interrupting production. This feature may be standard or may require a drive software upgrade from the manufacturer.
DC Bus Undervoltage Delay	This parameter allows the user to set a time delay for a DC bus undervoltage fault. If the duration of the undervoltage exceeds the delay time, the drive faults. Otherwise, the drive continues normal operation.

Parameters that Affect Recovery

Parameter	Parameter Description
Acceleration, Deceleration, Current Limit, and Torque Limit	These parameters are especially important after a sag ends and the drive attempts to recover. Inappropriate settings may cause the drive to trip or may not allow the process to recover.

However, automatic restart operations may only be used as outlined in NFPA 79. Equipment damage and/or personal injury may result if the automatic restart function is used in an inappropriate application. Motor-load control uses the motor's inertia or controlled acceleration/deceleration to ride through voltage dips. Detecting a loss of phase enables a drive to delay a fault condition and ride through the loss of phase. The DC link undervoltage trip point can be adjusted to enable a drive to ride through dips. After a voltage dip has occurred, rate of acceleration, rate of deceleration, current limit, and torque limit are parameters that affect the way a drive attempts to recover.

Recommended Settings for Chiller Controller and/or Motor Protection Relay for Optimal Power Quality Performance

Parameter	Function	Recommended Setting for Best PQ Performance	Note
Voltage Unbalance	Measure of allowable phase voltage unbalance	>3%	From ANSI C84.1, 98% of the electric supply systems surveyed are within the 0–3.0% voltage unbalance range.
Voltage Unbalance Time (sec)	Delay time in which unbalanced voltage must be present before chiller trips	5 seconds minimum	Instantaneous settings not recommended.
Current Imbalance	Measure of allowable phase current imbalance	20%–30%	For motors with service factors of 1.15 or greater.
Current Imbalance Time (sec)	Delay time in which imbalanced current must be present before chiller trips	5 seconds minimum	Instantaneous settings not recommended.
Auto Restart Option	Restarts chiller after shutdown	Enable	Always consider auto start features or auto start up of an adjacent chiller upon the fault of the unit that is running.
Single Cycle Dropout	Detects loss of power for a single cycle	Disable	Parameter not available on all chiller systems.
PB (Time)	Phase balance relay	5 seconds	Instantaneous settings not recommended.

General Recommendations for Chiller Controllers and Motor Protection Relay Settings

Voltage dips not only affect the electromechanical components like relays and contactors, they can also have an impact on the chiller's compressor motor protection relay (MPR). The MPR is used to protect the large compressor motor from damage caused by steady-state voltage or current unbalance conditions. The MPR can be a separate discrete component or the MPR functions can be built into the chiller's controller. Depending on the type, configuration, and software setting of the MPR, a voltage dip could be interpreted as a steady-state condition, thus causing the MPR to shut down the compressor motor. To prevent nuisance trips, the table on the left includes recommended settings for different MPR configurations.

LIGHTING

A variety of lighting fixtures can be found in commercial buildings. Understanding how power quality characteristics vary from one lighting technology to another is fundamental to ensuring sound up-front design.

Types of Lighting

There are a number of different lighting technologies employed in large commercial buildings:

Incandescent Lamps

Incandescent lamps use an electric current to heat a tungsten filament to a state of incandescence so that it produces visible light. The atmosphere around the filament is usually argon, an inert gas similar in atomic weight to oxygen. Some premium incandescent lamps use the rarer and more expensive krypton gas atmosphere, which

allows for roughly double the lamp life of a comparable argon-filled lamp. Operating voltage affects incandescent lamp operation. As voltage increases, more current passes through the filament, thereby increasing lumen output, efficacy, and color temperature. Lamp life is reduced, however. Conversely, as voltage is reduced, lamp life increases, while output, efficacy, and color temperature decrease.

Tungsten-Halogen Lamps

Tungsten-halogen lamps are incandescent lamps that are specially treated by the addition of a halogen material (iodine, chlorine, bromine, or fluorine) to the lamp atmosphere. The halogen material causes tungsten that evaporates from the filament during lamp operation to redeposit on the filament. This halogen cycle increases lamp life by decreasing lamp depreciation. Tungsten-halogen lamps also have a higher color temperature and efficacy. The halogen cycle requires very high lamp temperature inside a fairly small bulb. Consequently, most tungsten-halogen lamps use fused quartz glass bulbs that can withstand high operating temperatures. This gives rise to the common name "quartz lamps."

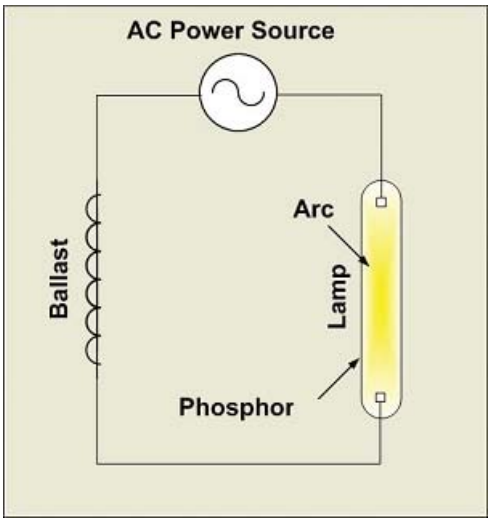
Discharge Lamps

In discharge lamps, an electric current is passed through a gas-filled tube, ionizing the gas so that electrons are released. Reabsorption of these electrons releases energy at very specific wavelengths. In some lamps, this energy is within the visible range, while in other cases a phosphor coating in the lamp is energized by the discharged energy. The phosphors react to the energy by glowing or fluorescing, thus creating visible light. Lamp color characteristics depend on gas type, pressure, and on the properties of the lamp's phosphor coating.

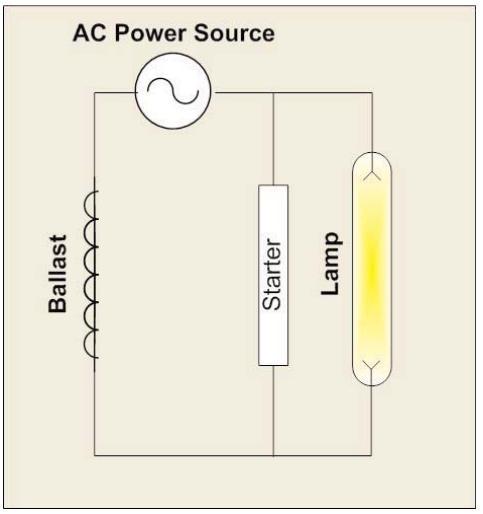
Discharge lamp technology is commonly applied to standard room lighting with fluorescent and metal halide lamps, high-powered area lighting with mercury vapor and sodium vapor lamps, and art or advertising signs with neon and argon lamps.

The electric current that flows through the gas is called an arc, because it jumps a gap between electrical contacts or electrodes at either end of the lamp. The arc must be maintained at specific voltage and current, or the gas pressure and temperature could escalate rapidly and cause the lamp to explode. As shown in the figure below, a device called a *ballast* is placed in the electric circuit to regulate the arc voltage and current for optimum lamp operation. In order to begin the arc, the gas must either be ionized by passing a very high voltage across the electrodes, or heated to operating temperature. This is called "starting," and the starting method varies with lamp type. An example starter is shown in the figure on the following page.

Fluorescent Lamp Circuit Configuration with Ballast



Arc Lamp Circuit Configuration with Starter and Ballast



Power Quality Characteristics of Fluorescent Lights

PQ Measurement	Description
Crest factor	Crest factor is related to the shape of the power wave delivered to the lamp by the ballast. High crest factors (the ratio of voltage peak to voltage mean) can reduce lamp life. Ballasts with crest factors below 1.7 are considered good.
Power factor	Power factor is the ratio of watts to volt-amperes of a ballast. This value measures how effectively the ballast converts input power into actual usable power. Some ballasts are equipped with a high power-factor designation, meaning they are equipped with a power factor of at least 0.90. A low or normal power factor ballast will have a power factor of less than 0.90—usually between 0.25 and 0.70.
Harmonic distortion	Harmonic distortion of the 60-Hz fundamental power waveform is an ongoing topic of concern and research. Lamp ballasts having total harmonic distortion below 20% are preferred; below 10% is considered excellent.

Fluorescent Lamps

Fluorescent lamps are by far the most common type of discharge lamp. They use a low-pressure, argon-mercury vapor atmosphere and a fluorescent mineral phosphor coating on the bulb wall to produce light. The sheer predominance of fluorescent lamps in commercial buildings demands the consideration of this load on the overall electrical environment.

Power Quality and Lighting

Power quality issues first gained prominence in the early 1980s with the first large-scale use of electronic ballasts for fluorescent lamps. Power quality manifestations caused by fluorescent light ballasts are listed in the table on the left. Power factor and harmonic distortion are the most relevant for commercial buildings.

Power Factor

Power factor, the ratio of watts consumed by an electrical component to the root-mean-square (RMS) volt-amperes delivered to it is an important characteristic of any electric device or equipment. Power factor affects current, which in turn affects the overall efficiency of the generation, transmission, and distribution of power from plant to customer. In lighting, power factor problems are usually associated with the ballasts used on fluorescent and high-intensity discharge (HID) lamps. Traditional electromagnetic ballasts require internal power factor correction so that the total load (ballast and lamp) has a power factor of 0.9 to 1.0. Normal power factor (NPF) ballasts, commonly found on compact fluorescent and low-wattage high-pressure sodium (HPS) lamps, traditionally have had power factors of 0.2 to 0.45 without correction. This means that a significant percentage of the current being drawn by the ballast is unused, as opposed to being used by the

A growing awareness on the part of the lighting community of the desirability of higher power factors has encouraged manufacturers to make available high-power-factor ballasts.

lamps or lost in the ballast. For example, although a 13-watt twin-tube lamp-ballast combination uses only 17 watts, it actually draws 34 VA if it has a power factor of 0.50. The utility must deliver this amount of apparent power, regardless of how much of it is used to light the lamp.

Buildings with low power factors require electrical distribution systems that are able to handle larger currents. Branch circuiting and overcurrent protection must be sized accordingly. Furthermore, low power factor can cause voltage drop, and in extreme cases, voltage dip. This may cause lights to dim, fuses to blow, and computers to crash. Fortunately, a growing awareness on the part of the lighting community of the desirability of higher power factors has encouraged luminaire manufacturers to make available high power factor (HPF) ballasts for most of their compact fluorescent and HID equipment. HPF ballasts are sometimes offered as standard luminaire components. More often, however, they are available only as an option and must be specified. High power factor generally is the rule, rather than the exception, for incandescent lamps and for magnetically ballasted full-size fluorescent and HID lamp-ballast systems.

However, electronic ballasts for full-size fluorescent lamps often have low power factors and may also generate high levels of current harmonic distortion (see the following section). Compact fluorescent lamp-ballast systems are also associated with low power factors. This is particularly true of the self-ballasted electronic products. Dimming systems and dimmable electronic ballasts can also reduce power factors due to line harmonics created by dimming.

Engineers can avoid power factor problems by minimizing the use of low power factor loads (a small portion of a building load can be low power factor without concern). In addition, they should carefully evaluate the power quality and harmonics impact (see below) of high-power control systems, such as very large solid-state dimming systems, variable speed drives for mechanical HVAC systems, mainframe computers, and other high-power devices employing switching devices in power supplies or controls.

Harmonic Distortion

Harmonic frequencies are higher multiples of the fundamental frequency (60 Hz in 120-VAC systems) superimposed on the sinusoidal waveform. For example, frequencies generated at 180 Hz are referred to as “third” harmonics. The sum of these multiple frequencies is referred to as total harmonic distortion (THD). THD caused by electronic fluorescent lighting ballasts has evolved into a major concern among members of the lighting community. Electronic ballasts increase lamp efficacy by converting 60-Hz power into high-frequency (20 to 40 kHz) alternating current.

Unfortunately, this action can introduce harmonic distortion in a building’s power line. It seems unfair, perhaps, that electronic ballasts have been singled out for so much attention during current debates on the harmonics issue. Similar harmonic distortion can be introduced by any electronic rectifying system or high-speed switching device (see Power Quality Impact on Commercial Customers section). THD is also produced by magnetic ballasts. THD is significant because when any combination of harmonics-generating devices composes a significant portion of a building or system load, the following undesirable effects may occur: imbalance and/or overloading of transformers and neutrals in three-phase distribution systems, caused by additive triplen (3rd, 9th, etc.) currents; power surges

Utilities are primarily concerned that there is a positive correlation between total harmonic distortion and power factor.

and spikes due to circuit resonance; or interference with electrical communications.

Distortion of the input voltage at the service location also results in reduced power factor. In an office building, for example, fluorescent lighting can constitute 35% to 50% of the electric load in the building. If all fluorescent lighting had electronic ballasts with 40% THD, the whole building's THD would likely fall between 5% and 8%. Power factor would be reduced, and problems with computers and other systems could result. In extreme conditions, high neutral currents caused by additive triplen currents could cause transformer damage and overheating in neutral conductors. The table below lists the expected THDs for various lighting technologies. In comparison, personal computers have a typical THD between 100% and 150%, while variable-speed drives are greater than 100%.[4]

Typical Total Harmonic Distortion for Different Lighting Technologies

Lighting Equipment	Typical THD
Magnetic energy-saving ballast, 2-F40	15–20%
Magnetic energy-saving ballast, 2-F96	25–30%
Screw-in electronic ballast compact fluorescent	125–175%
Industry standard electronic ballast, 2-FO32	20% or less
Low harmonic electronic ballast, 2-FO32	10% or less
Dimming magnetic ballast	40% maximum over dimming range
Solid-state dimming of magnetic standard ballast	100% maximum or greater over dimming range
Solid-state dimming of incandescent lamps	100% maximum over dimming range
Diode operation of incandescent lamps	100%[a]

[a]If a parallel lamp with opposite diode polarity is used, the THD drops to 0%.

Source: Power Quality Laboratory, Niagara Mohawk Lighting Research Laboratories, Rennsalaer Polytechnic Institute

THD and Power Factor

Utilities are primarily concerned that there is a positive correlation between THD and power factor. Harmonic currents generated by electronic ballasts, and other electronic devices, reduce power factor by distorting the sinusoidal wave shape of the current. By contrast, the electric current distortion produced by other devices such as magnetic ballasts and motors can introduce a phase shift between the voltage and current—also leading to reduced power factor. However, as long as there are no voltage-current phase-shift contributions to the power factor, the THD of a given electronic ballast may be as high as 48% and still maintain a power factor greater than 0.90.

THD in Recent Electronic Ballast Products

In order to minimize THD in electronic ballasts to generally acceptable levels, the National Electrical Manufacturer's Association (NEMA) and the American National Standards Institute (ANSI) have proposed limits of 33% for total harmonic distortion and 27% for triplens. Some utilities have independently established lower THD limits that electronic ballasts must meet in order to be eligible for rebate programs.

Using the latest technology, electronic ballasts have been designed with less than 10% THD. These products have been costly in the past, but increased competition among manufacturers has contributed to lower prices. Current electronic ballast products include models with THD as low as 5% with little or no cost increase over competing 20% THD products.

Elevators are susceptible to voltage fluctuations and interruptions and are exposed to internal transients caused by a highly inductive field winding.

ELEVATORS

The elevators are powered by a delta-connected DC generator mechanically coupled to an AC motor shaft. The generator's field voltage is controlled, producing a variable DC output. The variable DC is necessary to control the speed of the large DC motor that drives the elevator car. Elevators are susceptible to voltage fluctuations and interruptions and are exposed to internal transients caused by a highly inductive field winding, which can carry significant current depending on elevator loading and can produce a high-energy voltage transient if the current is interrupted.

Under controlled stop conditions, the field can be deenergized very quickly by diverting the energy through a surge suppressor connected across the field winding. The surge suppressor's function is to protect the control card from the regularly occurring transients that are associated with the operation of an elevator. When the elevator is at rest for shorter than 17 seconds, as when loading and unloading passengers, the DC motor acts as a brake and holds the car. If the car is at rest for longer than 17 seconds, such as when the last passenger leaves the car, a mechanical brake activates, relieving the DC motor of its load. This sudden change in current through the inductive field winding causes a transient voltage to appear, which can be sufficient to destroy the control card. An elevator's surge suppressor is designed to protect the exciter control card from these transients.

Tests have shown that voltage dips and interruptions cause transients that damage control cards. Voltage dips cause the controller's power supply to drop out. The table at top left lists general recommendations for power quality events that could either damage or cause the elevator to stop. To prevent damage caused by overheating, it's important to keep the elevator control room below 85°F.

Common Power Quality Events Affecting Elevator Operations

Internal transients	Install metal oxide varistors (MOVs) with sufficient clamping voltage to protect the control cards, while not clamping every transient. If the device were subjected to all of the transients associated with the normal elevator operation, its life would be shortened. If the problem persists after the MOV installation, another solution can be investigated. If cards are frequently damaged, check with the elevator manufacturer for transient protection solutions.
Voltage dips and interruptions	Condition the AC power to the main controller. This will significantly reduce the number of trips requiring a manual reset.

HARMONIC-GENERATING LOADS

The increasingly abundant use of nonlinear loads is changing the design requirements for building wiring. This change is especially true in large commercial buildings where three-phase circuits serve multiple single-phase nonlinear loads. Today, the increased use of nonlinear loads has significantly increased the load because these types of loads tend to remain turned on a high percentage of the time. Additionally, multi-outlet power strips have made possible a significant increase in the number of loads per outlet and thus a higher average plug load. Although most electronic equipment is energy efficient, the power factor is typically low when all the harmonic frequencies are taken into account. The resulting harmonic currents increase the amps per watt drawn

by nonlinear loads. An abundance of harmonic current, coupled with a high demand load and heavy plug loads, may consume any spare current-carrying capacity designed into the building transformers and conductors. In an extreme case, the electrical system in a commercial building may be overburdened if it is not designed to accommodate the large number of nonlinear loads. Moreover, typically codes do not take into consideration design procedures to protect wiring carrying harmonic-rich current.

The modern office is brimming with loads that draw nonsinusoidal currents. These nonlinear plug-in appliances include personal computers, printers, monitors, fax machines, and photocopiers. Nonlinear equipment such as fluorescent lamps with electronic ballasts and high-efficiency HVAC systems are also sources of harmonic currents in commercial buildings. The table below lists the current characteristics of single-phase appliances found in a typical commercial office building.

Current Characteristics of Single-Phase Equipment Found in Typical Office Buildings

Load	Operating State	Total Current (A)	60-Hz Current (A)	Harmonic Current (A)	Total Harmonic Distortion (%)	Harmonic Distortion Component (%)			
						3rd	5th	7th	9th
Fax machines	Idle	0.25	0.16	0.20	130	88	68	44	24
	Printing	3.75	3.74	0.22	6.00	5	2	2	0.3
	Sending	0.25	0.16	0.19	120	87	65	39	18
Clock radio	On	0.05	0.05	0.02	47	19	5	6	1
386 IBM-comp. PC	On	1.00	0.63	0.77	120	88	67	43	21
486 IBM-comp PC	On	1.00	0.56	0.83	150	93	80	61	42
Pentium PC	On	0.69	0.49	0.48	98	79	51	22	8
Macintosh PC	On	1.00	0.60	0.80	130	90	72	50	32
Laptop PC	On	0.16	0.09	0.13	140	92	78	60	40
PF-corrected PC	On	0.75	0.74	0.14	19	13	12	6	2
13-inch monitor	On	0.57	0.40	0.41	100	81	53	24	3
17-inch monitor	On	0.61	0.40	0.46	110	87	61	35	17
Phone switch	On	0.12	0.11	0.04	40	34	18	7	4
Photocopier	Idle	1.00	0.59	0.81	140	88	74	11	39
	Copying	10.5	10.35	1.76	17	5	13	7	1
VCR	Playing	0.19	0.11	0.16	150	91	77	62	47
Video system	On	0.93	0.60	0.71	120	86	65	42	21
Coffeemaker	Idle	0.85	0.85	0.03	3	2	3	1	0.3
	Brewing	11.70	11.69	0.35	3	2	3	1	0.5
Microwave oven	Cooking	9.00	8.21	3.69	45	43	12	4	2.2
Water cooler	Cooling	4.46	4.45	0.22	5	4.00	2	1	0.6
Pencil sharpener	Idle	0.03	0.02	0.02	97	37	4	11	14
	Sharpening	0.75	0.75	0.07	10	9	1	1	0.8
Electric typewriter	On	0.11	0.10	0.03	33	30	10	7	4
Incandescent lamp	On	0.45	0.45	0.01	3	2	2	1	0.4
Electronic fluorescent	On	0.12	0.08	0.09	120	85	64	40	22
Electronic fluorescent (power factor corrected)	On 0	13.00	13.00	0.02	15	3	9	3.7	3.1
Magnetic fluorescent	On	0.31	0.31	0.04	13	12	3	2	0.8
Desk fan	On	0.03	0.03	0.00	11	10	3	0.0	0.1
UPS #1	PC load	4.40	4.39	0.35	8	7	2	3	0.4
UPS #2	PC load	4.80	3.59	3.19	89	75	43	15	7
UPS #3	PC load	8.00	7.55	2.64	35	34	5	3	2
UPS #4	PC load	7.00	4.31	5.52	130	89	71	49	27
Laser printer	Idle	0.26	0.16	0.21	130	90	73	52	30
	Printing	0.40	0.27	0.30	110	85	61	34	10

The presence of even-numbered harmonics is not at all typical and may indicate a malfunction of the appliance.

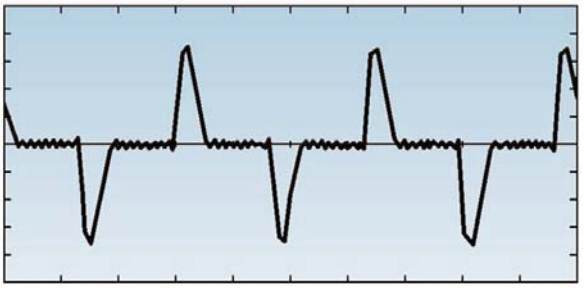
A few amps of very distorted current mixed with tens of amps of slightly distorted current should not overburden typical building wiring.

For single-phase electronic loads, the harmonic current may be higher than the fundamental current, indicating a total harmonic distortion of greater than 100%. Most of these machines generate odd-numbered harmonics (3rd, 5th, 7th, and so on). Note that, generally, the higher the harmonic number, the less the current produced. Harmonic currents are highest when many single-phase nonlinear loads such as computers are connected to a few branch circuits. In fact, multiple computer work stations and the like are responsible for the higher levels of current in commercial buildings. As shown in the table, the current drawn by single-phase electronic equipment is typically rich in third harmonic. The presence of even-numbered harmonics is not at all typical. In fact, even harmonic orders indicate either a malfunction of the appliance—which should be identified and removed or replaced—or the use of a half-wave rectifier such as an electric hand tool.

The relative power consumption of the electronic appliance and the percentage of THD determine how much the electronic equipment contributes harmonic current to the building wiring system. While some office loads may have a high percentage of distortion, the actual amount of harmonic current they contribute to the building wiring may be insignificant. For example, the personal computer with 150% current THD draws less than 1 amp of harmonic current. In contrast, the microwave oven with only 45% current THD draws almost 4 amps of harmonic current. Many small equipment, such as computers, may contribute very little to the total harmonic current in a wiring system. A few amps of very distorted current mixed with tens of amps of slightly distorted current should not overburden typical building wiring. The power-circuit design of an electronic appliance determines its current distortion characteristics. For example, each of the four UPSs in the table has a different front-end rectifier design. Consequently, the current harmonic distortion of each UPS ranges from 8% to 130%.

The typical computer, monitor, printer, and fax machine—all staples of the modern workplace—use switch-mode power supplies (SMPSs), which draw current as shown in the figure below.

Current Waveform of a Typical Switch-Mode Power Supply



Computer equipment and peripherals all use switch-mode power supplies.

The waveform of SMPS current tends to be very peaked and contains mostly third harmonic. The current harmonic distortion of one personal computer shown in the table is less than 20% because its power supply employs power factor correction and harmonic elimination circuitry—a design that was probably influenced by International Electro-technical Commission standards. Low-harmonic designs are expected to be used extensively in the near future.

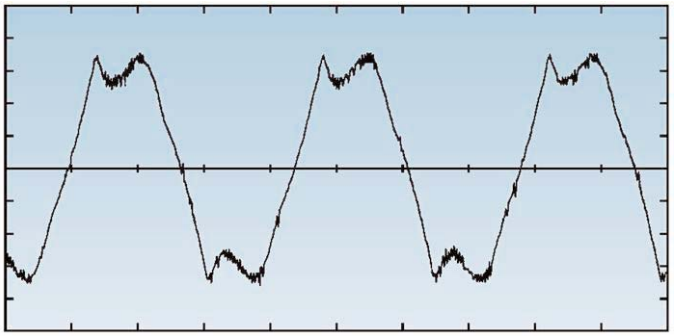
Lighting and Three-Phase Loads

In most cases, lighting and HVAC systems are connected to individual branch circuits, separating them from other loads in the building. Lighting in a modern office

Although compact fluorescent lamps are as efficient as 4-ft lighting systems, their current distortion can be significantly higher.

building provides a wide range of current waveforms and harmonic distortion. Energy-efficient fluorescent lighting is beginning to dominate all other types of lighting in commercial buildings. Both magnetic and electronic ballasts serving 4-ft fixtures can generate harmonic currents, but as seen earlier, levels are significantly lower than the typical computer. Industry standards for 4-ft fluorescent lighting require less than 30% current THD and a power factor greater than 0.9. The figure below shows the current waveform of a typical electronic ballast with a THD of 22%. Although compact fluorescent lamps are as efficient as 4-ft lighting systems, their current distortion can be significantly higher.

Electronic Ballast Current Waveform for Fluorescent Lighting

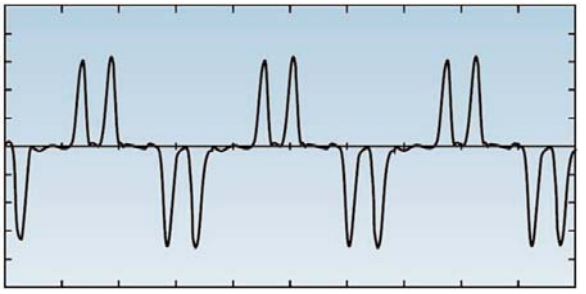


This waveform reflects the typical results of a ballast with a total harmonic distortion of 22%

HVAC loads are usually three-phase loads operating at either 230 or 400 V and have predominantly motor-type (inductive) loading characteristics. Some of the newer HVAC systems incorporate adjustable-speed drives (ASDs)—whose input power supplies are basically three-phase diode-bridge rectifiers—which inject harmonic currents back into the power distribution system. For three-phase loads, an unbalanced voltage will cause an increase in harmonic distortion, which is mostly 5th and 7th harmonic with little, if any, 3rd harmonic.

The current drawn by each phase of an ASD-driven HVAC system has the characteristic two-pulse waveform shown in the figure below.

Electronic Ballast Current Waveform for HVAC Systems

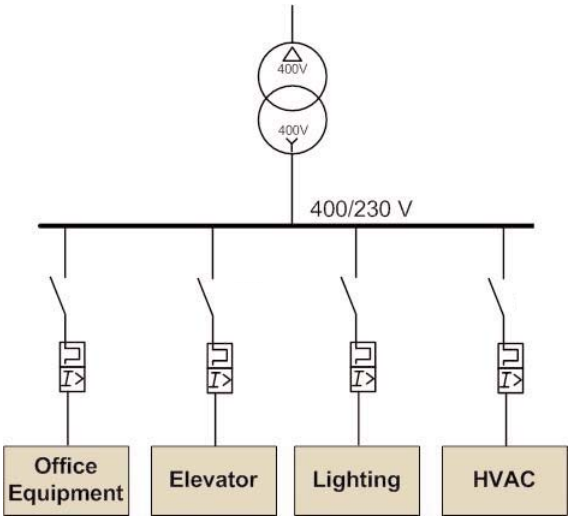


Each phase of an HVAC system driven by an adjustable speed drive produces this two-pulse waveform.

Wiring Configurations in Commercial Buildings

The effect of harmonic currents on the building wiring depends heavily upon the configuration of the wiring. The figure below is a typical wiring schematic for a commercial building.

Typical Commercial Building Power Distribution Single-Line

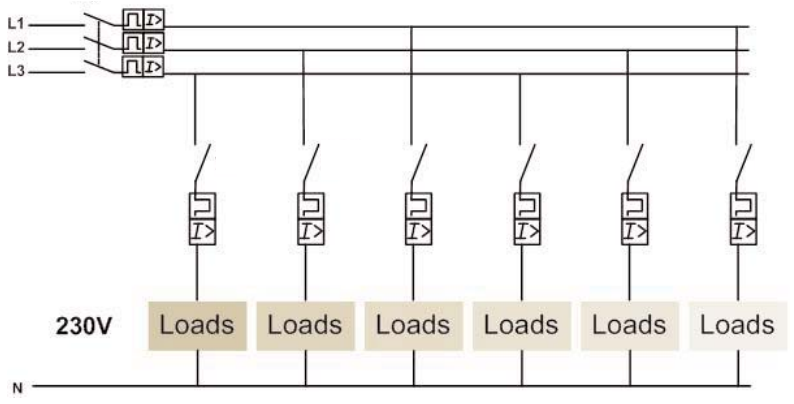


Typical loads for a commercial building include office equipment, conveyance, lighting, and building heating and cooling.

Large three-phase loads such as HVAC are served from motor-control centers or main power panels at 400 V. Lighting is often served from its own panel at single-phase 230-V office plug loads—derived phase-to-neutral connections. Although much of the harmonic current flowing from office equipment to the utility system will eventually cancel, harmonic current flowing in the branch circuits serving nonlinear loads may actually add in neutral conductors.

The plug loads in commercial office buildings are typically single-phase and connected from line to neutral, which can be either a separate neutral conductor or a neutral conductor shared by other loads in the circuit. The most common wiring configuration in Europe is a four-wire circuit with a shared-neutral conductor (see figure below).

Single-Phase Branch Circuits with a Shared Neutral Conductor



Loads within commercial builds often share a common neutral.

A balanced three-phase system with a shared-neutral conductor is also the most efficient configuration. Circuit losses can be as much as 40% lower with the shared-neutral configuration because the fundamental return currents cancel in the neutral conductor between office equipment. However, harmonic currents in this type of configuration may overload the neutral conductor, particularly if the conductor is undersized. Until recently, electric codes required neutral conductors to be one size smaller than the phase conductors.

Harmonic Effects on Building Wiring

The primary effect of harmonic loading on the building wiring is increased current, as much as double for loads with highly distorted currents. Highly distorted current also reduces the power factor and the spare current capacity of conductors. Because conductor heating depends upon the square of the current, building power system losses will also increase.

Losses in Conductors

Because conductors are resistive, any current flowing through them will generate heat. The amount of energy lost through heat by a conductor at a particular frequency depends upon the amount of RMS current flowing through the conductor and resistance of the conductor at that frequency. Harmonic currents usually add to the RMS current flowing in building wiring, thus increasing the amount of energy loss. For highly nonlinear loads such as personal computers, the RMS current due to harmonics could be as high as the fundamental current.[5]

Losses in Transformers

Nonlinear loading may increase heating in transformers because the RMS current is usually higher per watt with nonlinear loads. Additionally, the higher frequencies in nonsinusoidal current will heat transformer components more than an equivalent amount of sinusoidal current. Step-down transformers connected in a delta-wye configuration and serving single-phase nonlinear loads can act as a filter, protecting

The results of harmonics created by office equipment are overloaded undersized neutral conductors, inadequate filtering caused by undersized transformers, and energy losses through the neutral conductor and transformers.

the upstream part of the building wiring. Load losses due to harmonics are usually significant. These losses are related to current in both the primary and secondary windings. Load loss is the sum of all current-related losses, including copper losses (I^2R_{AC}) and eddy-current losses. Copper losses depend upon the load current and AC resistance of the windings (DC, skin-effect, and proximity-effect resistances). When the currents flowing in the windings of a transformer are rich in harmonics, the induced eddy-current losses in the windings increase significantly and may be many times higher than the eddy-current loss due to 60-cycle current. The table below shows the load losses for a typical delta-wye transformer. The total losses nearly triple for nonlinear loads with the same real power (watts).

Circuit-Breaker and Connector Heating

Harmonic currents affect circuit breakers and connectors in subtle ways. Generally, harmonic currents heat circuit breakers and related connectors. Peak harmonic current and vibrations induced by harmonic currents can also heat connectors and contacts. Additionally, voltage distortion resulting from current distortion can heat the coils of a circuit breaker. When circuit breakers are subjected to continuous nonlinear-load current near their rated thermal trip, a transient or small increase in loading may trip them. When reset, they are likely to be cooler, so the cycle may begin again. Consequently, some overload problems go unnoticed for a long time until more definite symptoms appear. Loose connectors may cycle between hot and cold as the load changes state—for example, as equipment is turned on or the heater elements of printers and copiers cycle on and off. This cycling loosens the connectors even more, which contributes to resistance and thus heating.

In summary, the results of harmonics created by office equipment are overloaded undersized neutral conductors, inadequate filtering caused by undersized transformers, and energy losses through the neutral conductor and transformers. By installing neutral conductors sized one gauge larger than the phase conductors, building designers and engineers can adequately mitigate the effect of harmonic currents on shared-neutral conductors. Additionally, a rating system for sizing transformers in a world of harmonic currents has been in place for several years and has been effective in measuring and reducing the potential for overloading transformers. In the end, the total energy losses caused by harmonic currents tend to go unnoticed in the power bill because of the increased energy efficiency of many harmonic-generating loads. Office equipment manufacturers have not been idle. With every new generation of office equipment, they have an opportunity to improve their products. For example, manufacturers are beginning to incorporate power-factor correction circuits into their power supplies. Therefore, future generations of energy-efficient electronic appliances may generate such low levels of harmonic current that even buildings with modestly sized neutral conductors and transformers would be able to carry the currents drawn by office appliances.

Typical Transformer Losses with Linear and Nonlinear Loads

Type of Load Loss	Losses (Watts)	
	Linear Load (PF = 1.0, ITHD = 0%)	Nonlinear Load (PF = 0.64, ITHD = 100%)
Copper Loss = $\Sigma I_h^2 R_{AC}$	1500	2986
Eddy-Current Loss $P_{EC} = \Sigma I_h^2 h_{AC}$	75	1336
Total Load Loss $P_{LL} = \Sigma I_h^2 R + P_{EC}$	1575	4322

Assumptions: Three-phase delta-wye transformer is rated at 112 kVA; load is 60 kW.

NOTES

1.European Commission, "Towards a European Strategy for the Security of Energy Supply," Green Paper (October 2001), p. 4, available from http://ec.europa.eu/.

2. EPRI, *Roadmap for Power Quality Mitigation Technology Demonstration Projects at Commercial Customer Sites*, TR-114240 (Palo Alto, CA: EPRI, 1999)

3. M. Stephens and C. Thomas, *Protecting Process Water Cooling Systems Against Electrical Disturbances, Power Quality for Utilities to Support Commercial and Industrial Customer Program*, EPRI Technical Update 1002283 (2003).

4. EPRI, "Commercial Office Wiring Nonlinear Loads Harmonic-Related Heating," Commentary No. 1, EPRI Power Quality Testing Network TC-107163 (December 1996).

5. EPRI, "Avoiding Harmonic-Related Overload of Shared-Neutral Conductors," Application No. 6, EPRI Power Quality Testing Network TA-106576 (April 1996).